TURBULENT CONVECTIVE HEAT TRANSFER IN AN INCLINED CYLINDER WITH LIQUID SODIUM

Mamykin Andrei, Vasiliev Andrei, Khalilov Ruslan, Kolesnichenko Ilya & Frick Peter
Institute of Continuous Media Mechanics, Perm, Russia

Abstract The natural turbulent convection of liquid sodium in a cell with end heat exchangers providing a fixed temperature drop is investigated experimentally. The cell is a straight thermally isolated tube with inner diameter D = 96 mm and length L ≈ 20D. Experiments are carried out for a fixed Rayleigh number $Ra = 2.4 \cdot 10^6$ and for different tube orientations with respect to the gravity. A strong dependence of power transferred along the tube on the inclination angle is discovered: Nusselt number varies by an order in the investigated range of angles with a maximum approximately at 65^o to the vertical. Presented characteristics of the large-scale circulation (LSC) and turbulent temperature fluctuations demonstrate the fact that the convective heat transfer is mainly determined by the velocity of the LSC.

Key words: Natural convection, turbulence, liquid metal, heat and mass transfer.

INTRODUCTION

The interest in heat and mass transfer in liquid metals is largely stimulated by their application as coolants in nuclear reactors [1], fusion reactors and space power plants. Sodium is used as a coolant in a fast neutron reactor plants.
From operational experience of Russian BN-350 and BN-600 it is known [2] that in case of favorable pipeline layout a natural convection of sodium may occur, which leads to heating of pipelines and increasing of heat loss. Therefore, the experimental studies of natural convection of sodium in the long closed cylindrical vessels oriented at different angles with respect to gravity are becoming very required. The results of these studies can be applied for the designing of new cooling systems and for verification of CFD codes used in nuclear power engineering.
For long vessels there is a strong dependence of the intensity of heat transfer along the cell on inclination angle (for example, long tubes filled with liquid helium Pr ≈ 0.7 [3] or thermosyphons filled with water Pr ≈ 7 [4]). The case of small Prandtl numbers (liquid metals with Pr ≈ 0.01 or less) remains the least studied, even for short cylinders [5], and there is no experimental works on natural convection in the long cylinders found by authors.

EXPEREMENTAL SETUP

We study the convection of sodium in cylindrical tube of length L = 1980 mm and diameter D = 96 mm made of stainless steel (the wall thickness is 8 mm) closed by copper heat exchangers (at one end an electric heater and the other a cooler). The cooler consists of a copper plate with 474 copper rods of length 200 mm and diameter 5 mm screwed into it. These rods are placed in a box and forcibly blown by air with controlled flow rate. The cavity has an expansion tank. The cylinder and expansion tank are fully insulated with mineral wool and aluminum foil (the averaged thickness of the wool is 30 mm). The cylinder is placed on a frame, on which it can be mounted at a given angle (α = 0 - 90° form vertical). For inclined and vertical positions, the heater is below the heat exchanger, i.e. we study the case of heating from below. Chromel-alumel thermocouples with an isolated junction of diameter 1 mm are used for temperature measurements. There are 22 thermocouples immersed in sodium. The maximum sampling rate for each thermocouple is 75 Hz. All measurements are carried out for fixed average temperature of sodium T = 150 °C and temperature difference between the end plates ΔT = 40 °C. Thus, the three of four control parameters (Rayleigh number Ra, Prandtl number Pr and the aspect ratio Γ) are fixed $Ra = {}^{g\beta D^3 \Delta T}/_{\nu\chi} = 2.4 \cdot 10^6$, $Pr = {}^{\nu}/_{\chi} = 0.0089$, $\Gamma = {}^{D}/_{L} = 0.049$, where g is the gravitational acceleration, β is the thermal expansion coefficient, ν is the viscosity, and χ is the thermal diffusivity. Cross-correlation velocimetry are applied for estimation the mean velocity of LSC. In this technique the temperature-time records from a pair of thermocouples, one downstream of the other, are cross-correlated to determine the flow's preferred mean velocity [6].

RESULTS AND DISCUSSIONS

Experiments are carried out in a stationary mode for 13 orientations of the tube. Design of the setup does not allow controlling the heat removal through the cooler. The measured quantity is the electric power Q consumed by the heater. Since the temperature of all components of the apparatus substantially exceeds the ambient temperature, it is clear that some of this power is dissipated through the insulation. Additional measurements of electrical power which is required to maintain identical temperature T = <T> = 150 °C of both heat exchangers are carried out to estimate a heat leak Q_l

(an electrical heating of the cooler is implemented for this purpose; there is no air circulation through the cooler). The heat transport is usually expressed in terms of the Nusselt number $Nu = {}^{4(Q - Q_l)L}/_{\pi D^2 \lambda \Delta T}$, where λ is the thermal conductivity of the fluid in the absence of convection. Fig. 1a presents a dependence of the Nusselt number Nu on inclination angle α: in case of vertical position Nu = 11, it increases to Nu = 124 at α = 65° and then decreases to Nu = 45 at α = 90°. Thus, the convective heat transfer in a tube inclined at 65 degrees to the vertical, almost three times higher than in a horizontal one with the same temperature difference and more than ten times higher than the convective heat flux in a vertical one.

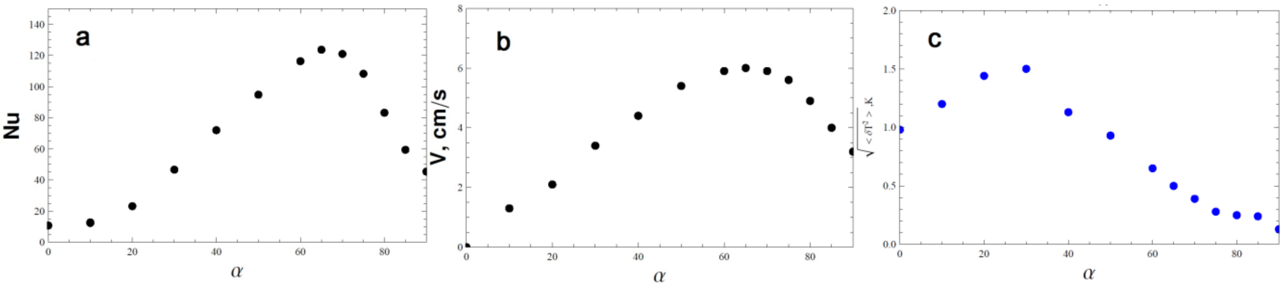

Figure 1. Nusselt number (a), average value of the velocity longitudinal component of sodium (b) and rms temperature fluctuations (c) as a function of inclination angle α.

It is interesting to study the structure and nature of established convective flow in the tube. The results of measurements are revealed that in all cases, except strictly vertical position, the averaged large-scale flow is observed in the tube. The corresponding dependence of averaged velocity V of the LSC on the inclination angle α is presented in Fig.1b. It can be seen that the dependence Nu (α), in general, reproduces the form of the function V (α), which indicates that it just a LSC defines the power transferred along the tube. However, one can see that in the region of small angles the flow velocity increases with angle faster than the heat transfer and maximum near α = 65° in the function Nu (α) is sharper. Turbulence is another factor which is influence on the convective heat transfer. Large-scale flow velocity reaches 0.06 m/s, which gives an estimation of the Reynolds number Re = VD/ν = 10000 indicating the presence of a developed small-scale turbulence in the flow. RMS value of temperature fluctuations as a characteristic of turbulence intensity are shown in Fig.1c. This figure shows a high level of temperature fluctuations in the vertical position, which become even more intense with a slight inclination of the tube, reaching a maximum at α = 20 - 30°. A further increase in the angle of inclination leads to a monotonous decrease in the level of fluctuations. Amplitude of the temperature fluctuation in the case of horizontal position drops on an order in comparison with it in the case of vertical position. Increasing of turbulent fluctuations, in the judgment of the authors, is the reason why flow velocity increases with angle faster than the heat transfer in the region of small angles - turbulence amplifies heat transfer between the counter streams of hot and cold liquid.

It should be noted that dependencies of the Nusselt number on inclination angle of the tube like shown in Fig. 1a, have been already observed for fluids with Prandtl number of the order of unity. Experiments with liquid helium (Pr ≈ 0.7) encapsulated in a tubes with length equals to 10 - 50 diameters and Rayleigh numbers $Ra = 5 \cdot 10^6 - 10^8$ indicates a maximum at approximately the same angles of inclination, as in the present case of liquid sodium. However, in case of helium natural convection the maximum heat flow exceeds heat flow in the vertical tube by 4 - 5 times, while in the case of sodium this ratio reaches the number of 11 times.

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